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Research note

Experimental investigation of the dielectric barrier discharge using design of experiments

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Dielectric barrier discharge;
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Modelling;
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Abstract Many experimental and numerical studies were devoted to Dielectric Barrier Discharge (DBD) in air, but no mathematical models were proposed, either for current or for power. As they depend on several parameters, it is difficult to find a formula that considers many factors. The aim of this paper is first to make a brief comparison between surface and volume DBD, and second to model the current and power of a DBD in a "multipoints-plane" electrode system, using the methodology of experimental design. Three factors were considered: inter-electrode distance, distance between adjacent points, and thickness of the glass dielectric barrier. A double Composite Centred Faces experimental design (CCF) was carried out. The obtained results made it possible to propose mathematical models and, therefore to study interactions between various factors.

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1. Introduction

Dielectric Barrier Discharge (DBD) in air has been the subject of many research studies [1–3]. This physical phenomenon is nowadays well known, and many researchers have contributed to the comprehension and explanation of the micro-discharge mechanism [4–7].

Many factors affect the DBD, such as electrical, geometrical and climactic parameters. Nowadays, the influence of each one of these is well-known, but we do not appreciate the interactions existing between these factors. For example, when the inter-electrode distance and thickness of the dielectric barrier vary simultaneously, one has a larger influence than the other. Thus, we make use of experimental design methodology, being a powerful tool for modelling and analysing interactions between factors. We opted for a configuration of electrodes consisting of a high voltage multipoint electrode and planar dielectric and metallic electrodes. In this paper, we examine three factors: inter-electrode distance, distance between adjacent points and thickness of the glass dielectric barrier. We first make a brief comparison between surface and volume DBDs.

2. Surface and volume DBD

An electrostatic voltmeter and an oscilloscope were used to measure the applied high voltage and the current. The high voltage was delivered by a power supply of voltage 6 kV, current 30 mA and frequency 22 kHz. A 100 Ω resistor is placed in series with the circuit, whose voltage drop is visualised by the oscilloscope to measure the current generated by the DBD.

We have accomplished, in this section, an experimental study to compare two different electrode systems: "point-to-plan" and "surface DBD". The point electrode is sharp, has a radius of 150 μm, and is placed above the dielectric barrier at a distance of 1 mm. The surface DBD is obtained using two bands of adhesive aluminium (length: 10 cm, width: 2 cm) as electrodes, each placed on a different side of the dielectric. The dielectric barrier is glass, having a thickness of 3 mm. The two configurations are schematically shown in Figure 1.

Figures 2 and 3 show diagrams of voltage drop across the resistor corresponding to the two configurations for an applied voltage of 6 kV.

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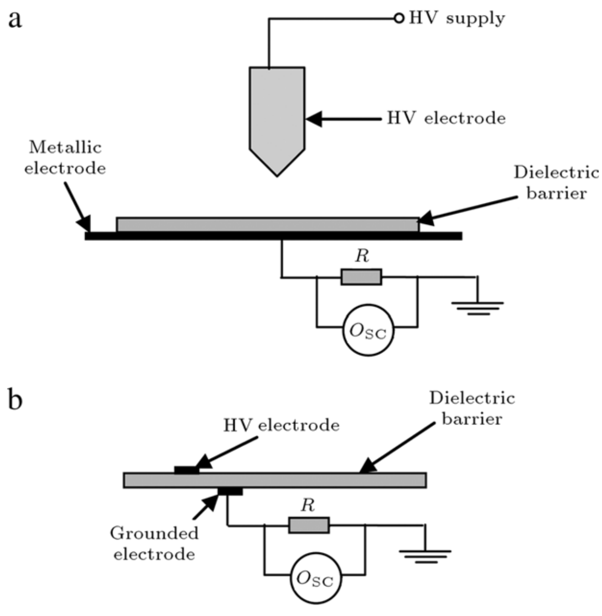

Figure 1: Schematic representation of the experimental device. (a) Volume DBD; and (b) surface DBD.

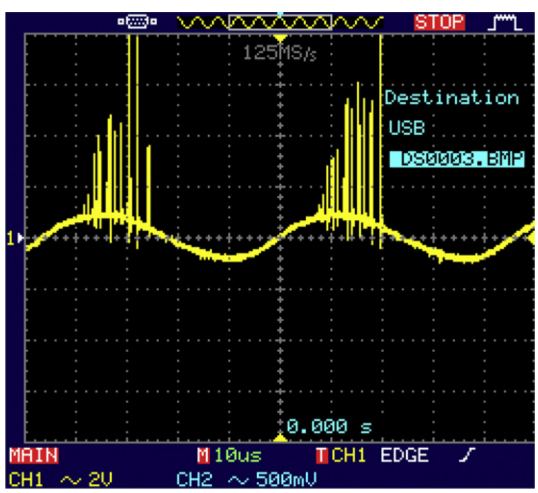

Figure 2: Diagram of the voltage drop across the resistor of the volume DBD.

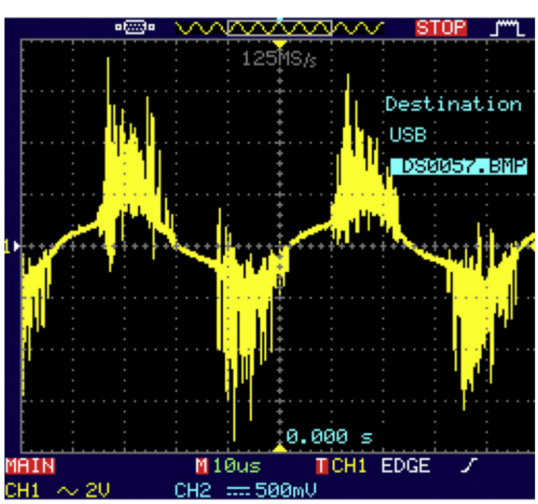

Figure 3: Diagram of the voltage drop across the resistor of the surface DBD.

We can notice from the diagrams that there exists a difference between the volume and surface DBD. The density of micro-discharges is higher for surface DBD, because they occur over the entire length of the electrode, which is equal to 10 cm. However, in the case of a pointed electrode, the pulse amplitude is greater, the current exceeding 80 mA for some pulses. Furthermore, there is no discharge in the negative alternation for the volume DBD. For the surface DBD, the discharge occurs on a greater surface area, the effect of DBD "memory" is more important and, therefore, the discharge is more easily initiated in negative alternation.

3. Experimental design methodology

The methodology of the experimental designs makes it possible to determine the number of experiments to be achieved, according to a well defined objective, to simultaneously study several factors, to reduce dispersion related to measurements, to appreciate the effects of coupling between factors and, finally, to evaluate the respective influence of the factors and their interactions [8–11]. Many papers deal with the application of this methodology in electrical and electrostatic processes [12–20].

3.1. Development of the method

Finding mathematical models of good quality with minimum effort depends on the way in which intervals of input factors are selected. This method can be used as follows [21,22]:

- Selection of the most interesting and influential factors.
- Determination of maximal, minimal and central values of each factor.
- Carrying out a matrix of experiments with all possible states and corresponding responses.

Before starting the experiments, it is necessary to set the best and most suitable design, which can model the process with the most possible precision. In this paper, we chose the double Composite Centred Faces design (CCF), which gives quadratic models. It is possible to determine a quadratic dependence between the output function to optimize (response) and the input variables, u_i $(i = 1, \ldots, k)$ (factors):

$$y = f(u_i) = c_0 + \sum c_i u_i + \sum c_{ij} u_i u_j + \sum c_{ii} u_i^2.$$

Knowing that Δu_i and u_{i0} are, respectively, the step of variation and the central value of factor i, the reduced centred values of input factors may be defined by the following relation:

$$x_i = (u_i - u_{i0})/\Delta u_i.$$

With these new variables, the output function becomes:

$$y = f(x_i) = a_0 + \sum a_i x_i + \sum a_{ij} x_i x_j + \sum a_{ii} x_i^2.$$

The coefficients are calculated by a data-processing program, using the least mean squares method.

3.2. Software MODDE 5.0

We used software MODDE 5.0 (Umetrics AB, Umea, Sweden), which is a Windows program for the creation and evaluation of experimental designs [23]. The program assists the user in interpretation of the results and the prediction of the responses. It calculates the coefficients of the mathematical model and identifies the best adjustments of the factors to optimize the process.

Moreover, the program calculates two significant statistical criteria, which makes it possible to either validate the math-

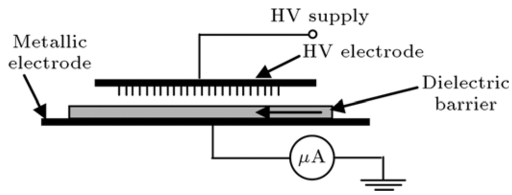

Figure 4: Schematic representation of the experimental device.

ematical model or not, symbolized by R^2 and Q^2. The former is called the goodness of fit, and is a measure of how well the model can be made to fit the raw data; it varies between 0 and 1, where 1 indicates a perfect model and 0 no model at all. The latter is called goodness of prediction, and estimates the predictive power of the model. Like R^2, Q^2 has the upper bound 1, but its lower limit is minus infinity. For a model to pass the diagnostic test, both parameters should be high, and preferably not separated by more than 0.2–0.3.

4. Results

As the principal application of DBD is ozone generation whose efficiency depends on generated power, this latter is the response to optimize. We use, for this experimental purpose, a typical multipoint-to-plane set-up, energized with a 6 kV, 30 mA and 22 kHz power supply. The power was measured using a current–voltage product in RMS values. The experimental bench is shown in Figure 4.

The multipoint electrode consist of a rectangular matrix of sharp needles, the distance, d_p, between two adjacent needles is constant. According to preliminary experiments, three factors were considered as most influential for which we determine limits of variation:

- Distance between adjacent points d_p : $d_{p_{\min}} = 10$ mm and $d_{p_{\max}} = 30$ mm.
- Inter-electrode distance d_e : $d_{e_{\min}} = 50$ mm and $d_{e_{\max}} = 70$ mm.
- Thickness of glass dielectric barrier e : $e_{\min} = 30$ mm and $e_{\max} = 50$ mm.

Figure 5 shows experiments of a CCF design with 3 factors. It consists of 8 experiments located at the tops of the cubes (square points $A, B, \ldots, H$), 6 experiments located at the centres of the cube faces (round points $a, b, \ldots, f$) and 3 identical experiments done at the central point, M (star point). Thus, a double CCF design with 3 factors includes 2×17 experiments.

Obtained results of power P are given in Table 1 in which the results of both factorial and composite designs are also given.

Once experimental values of power P are measured, software MODDE 5.0 checks whether experimental results are "reasonable" and detects any "doubtful" measurement result. The graph represented in Figure 6 shows that all experiments are located inside the validation limits of results, which makes it possible to validate the experimental results.

The statistical tests lead to a valid mathematical model, since R^2 and Q^2 reach high values: $R^2 = 0.94$ and $Q^2 = 0.88$.

The mathematical model suggested by MODDE 5.0 is:

$$P = 74.2 - 24.52d_p^* - 7.72d_e^* - 0.12e^* + 9.11d_p^{*2} + 3.51d_e^{*2} + 1.91e^{*2} + 12.45d_p^*d_e^* + 1.62d_p^*e^* - 0.25d_e^*e^*.$$

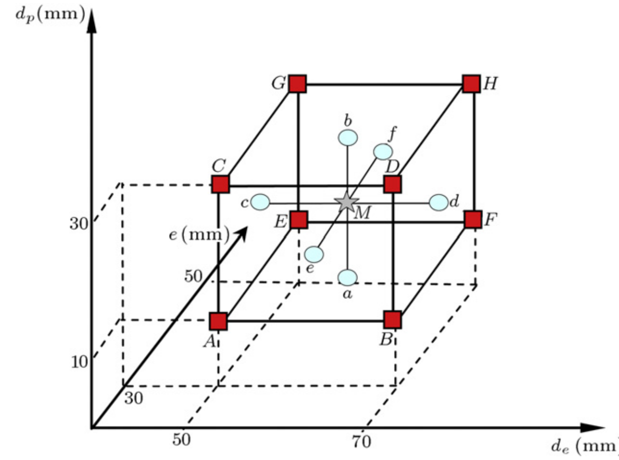

Figure 5: Diagram of experiments of a double CCF design with 3 factors of d_p (distance between adjacent points (mm)), d_e (inter-electrode distance), and e (thickness of the glass dielectric barrier).

Table 1: Results of the double CCF experimental design.

Exp. no	d_p (mm)	d_e (mm)	e (cm)	P (W)
1	10	50	30	144.0
2	10	50	30	136.0
3	10	70	30	64.0
4	10	70	30	51.2
5	10	50	50	92.8
6	10	50	50	92.8
7	10	70	50	64.0
8	10	70	50	67.2
9	30	50	30	132.0
10	30	50	30	136.0
11	30	70	30	70.4
12	30	70	30	57.6
13	30	50	50	92.8
14	30	50	50	89.6
15	30	70	50	64.0
16	30	70	50	67.2
17	20	60	40	102.4
18	20	60	40	102.4
19	20	60	40	70.4
20	20	60	40	54.4
21	20	60	40	80.0
22	20	60	40	70.4
23	20	50	40	76.8
24	20	50	40	80.0
25	20	70	40	76.8
26	20	70	40	73.6
27	20	60	30	76.8
28	20	60	30	73.6
29	20	60	50	73.6
30	20	60	50	73.6
31	10	60	40	76.8
32	10	60	40	76.8
33	30	60	40	73.6
34	30	60	40	76.8

5. Discussions

Breakdown in a gap with insulated electrodes normally occurs in a large number of individual tiny breakdown channels, referred to as micro-discharges. By applying an electric field larger than the breakdown field, local breakdown in the gap is initiated. In an equivalent circuit, this is symbolized by closing a switch and forcing some of the current through the plasma filament whose resistance, $R(t)$, rapidly changes with time. In reality, growing electron avalanches quickly produce such a

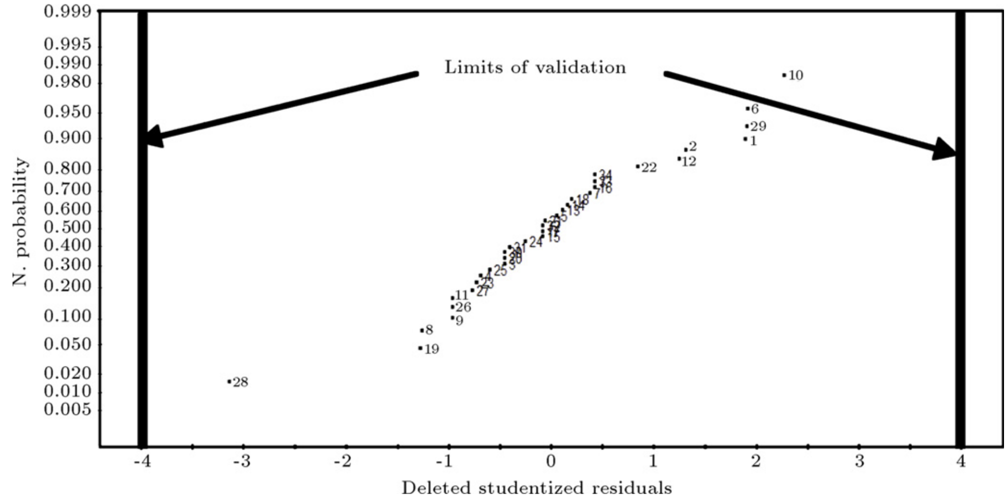

Figure 6: Graph for validation of measurements.

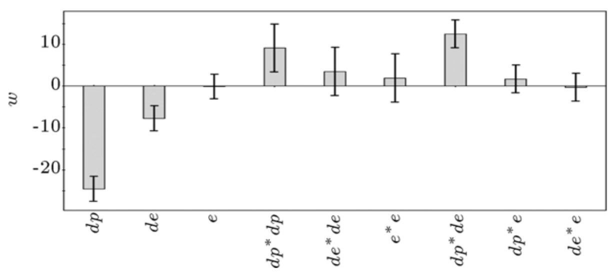

Figure 7: Plotted coefficients for power modelling.

high space charge that self-propagating streamers are formed. The current flows through the conductive channel, bridging the electrode gap peaks. Subsequently, charge accumulation at the dielectric surface reduces the local electric field to such an extent that ionization stops within a few nanoseconds and the microdischarge is choked.

Values of the coefficients associated with the factors in the mathematical model show the degree of influence of each factor. The coefficients are also plotted in Figure 7. It arises from the proposed mathematical model that within the variation limits of the selected intervals, the separation distance between adjacent points is the one which has the most effect. The thickness of the dielectric seems to have little influence compared to the other parameters. All the factors are negative, which means that minimizing the separation distance between adjacent points, d_p, inter-electrode distance, d_e, and the thickness of the dielectric, e, leads to higher power values. Among the different interactions between the factors, it is noticeable to see that there exists a strong interaction between d_p and d_e, and a poor interaction between d_e and e.

The program also has an optimization option, which gives the most optimal values of factors to obtain maximal power. Proposed optimal values are $d_p = 10$ mm, $d_e = 50$ mm and $e = 30$ mm.

The contour plots obtained for the model are represented in Figure 8. They point out that power is highly influenced by the factors "distance between points" and "inter-electrode distance". On the contrary, the power seems to be very little influenced by the thickness of the dielectric when compared with inter-electrode distance influence.

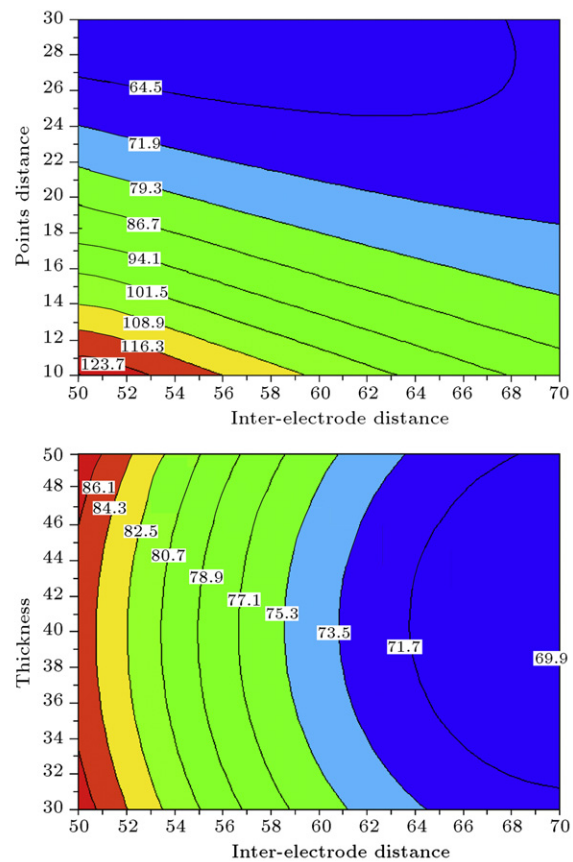

Figure 8: Contour plots of the model computed with MODDE 5.0.

6. Conclusion

Dielectric barrier discharges remain the subject of several applications in industry, where power is the first criteria requested by users. As it is difficult to find a formula for the power, because it depends on numerous factors, the aim of this paper consists of modelling it using the methodology of experimental designs. Several factors were considered in this study: inter-electrode distance, distance between adjacent points and thickness of the glass dielectric barrier. Obtained results made it possible to propose a mathematical model and to analyze the various interactions between these factors. Furthermore, we made an experimental study to compare the surface and volume DBD and noticed that the first one is more powerful.

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